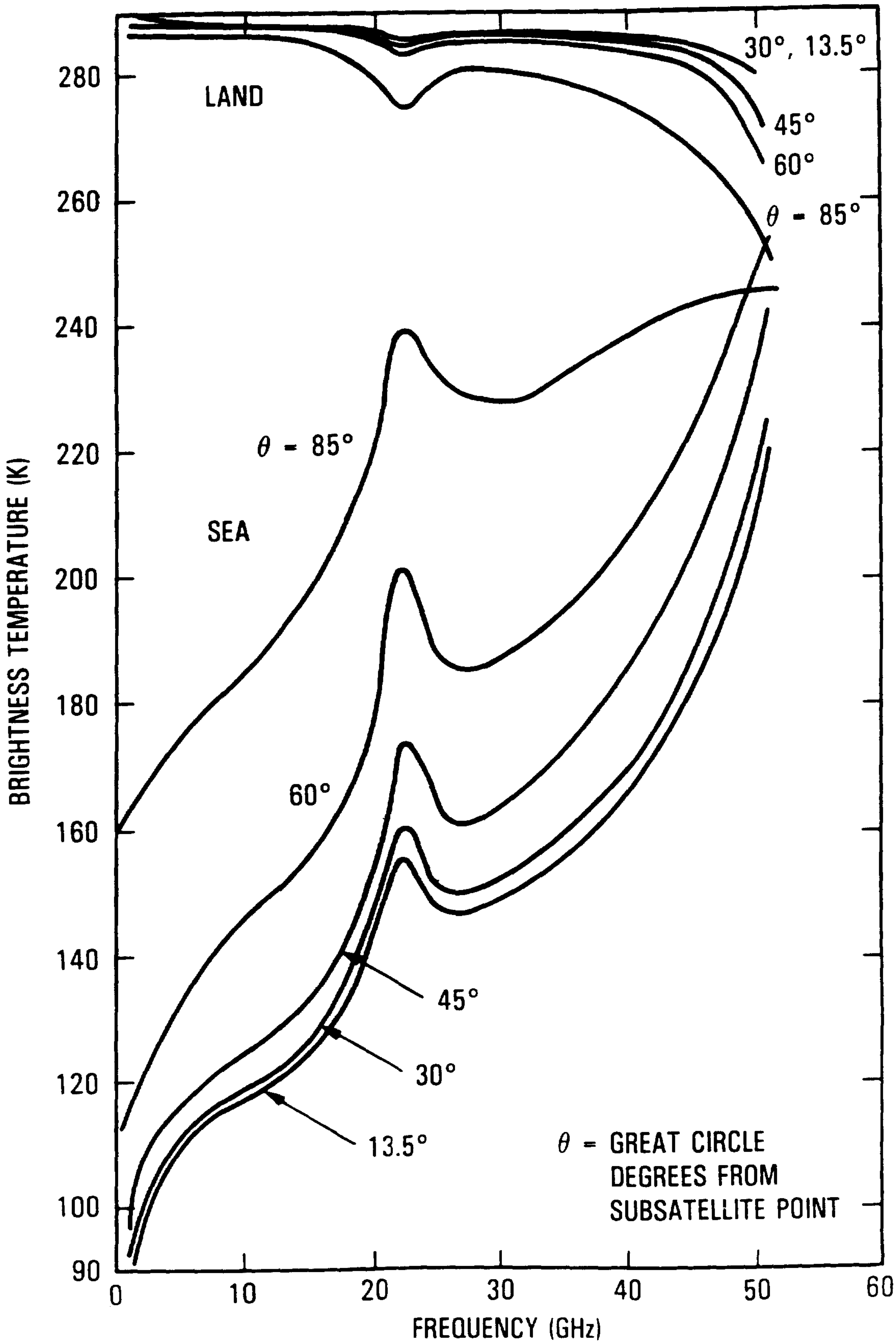

Figure 6.9-2. Brightness Temperature Contributions for Land and Sea, as a Function of Frequency and Latitude.

$$T_s = 0.6(275) + 0.4(185) = 239 \text{ K}$$

A more exact determination involves weighting each incremental area in the antenna beam by the appropriate off-boresight antenna gain. The additional accuracy is usually not necessary, however, since current satellite receiver noise temperatures are typically 1000 K or higher, and the incremental difference in the total system noise temperature would likely be very small.

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CHAPTER VII

APPLICATION OF PROPAGATION PREDICTIONS TO EARTH/SPACE TELECOMMUNICATIONS SYSTEM DESIGN

7.1 INTRODUCTION

A function of the satellite communication system designer, or system engineer, is to interface between the source of system requirements (i.e., the user) and the sources of performance data. Stated in terms of the present problem, the system engineer uses propagation and other technical data to achieve a system design that will meet the requirements specified by the user. These requirements are specified in terms of a gross quantitative need (e.g., number of channels), a quantitative expression of performance (e.g., percent of time available), and, sometimes, more qualitative expressions (e.g., "highly reliable"). Even though both the propagation data and the requirements are often expressed in terms of cumulative probability distributions, it is not always straightforward to relate one distribution to the other. The correspondence between a given propagation phenomenon and system performance may be complex. The purpose of this chapter is to relate propagation data to system performance parameters. It should allow the system engineer to perform the analyses telling how well requirements are met by a given system design, thereupon enabling the system engineer to modify that design if necessary. First (in Section 7.2), the various ways of specifying performance criteria for different kinds of systems are discussed. In addition, examples of specific satellite communication systems are discussed. Procedures for designing such systems are then described in section 7.3.

There are engineering disciplines for which true synthesis procedures exist, but the design of complex systems with interactive elements is usually not a true synthesis. Instead, iterative analyses are performed, starting with a preliminary design choice, until the refined design can be shown by analysis to meet the requirements. The application of this philosophy of system design or synthesis to satellite communications is summarized here and detailed in Section 7.3.

The system design procedure is based on criteria that take the form of discrete cumulative probability distribution functions of performance. The steps necessary to go from this set of performance requirements and propagation statistics to a system design are (see Figure 7.1-1):

INITIAL PHASE

1) Establish system performance requirements (discrete distribution of baseband/digital performance).

2) Apply modulation equations to convert system performance requirements to discrete distribution of the received composite CNR (carrier-to-noise ratio).

3) Prepare initial design with parameters sized according to free space propagation conditions (apply power budget equations).

DESIGN SYNTHESIS AND TRADE OFF PHASE

4) Employ

   a) Composite CNR distribution from step 2

   b) System architecture

   c) Multiple Access equations

   d) Availability sub-allocation philosophy

   to develop distribution functions for CNR on each path.

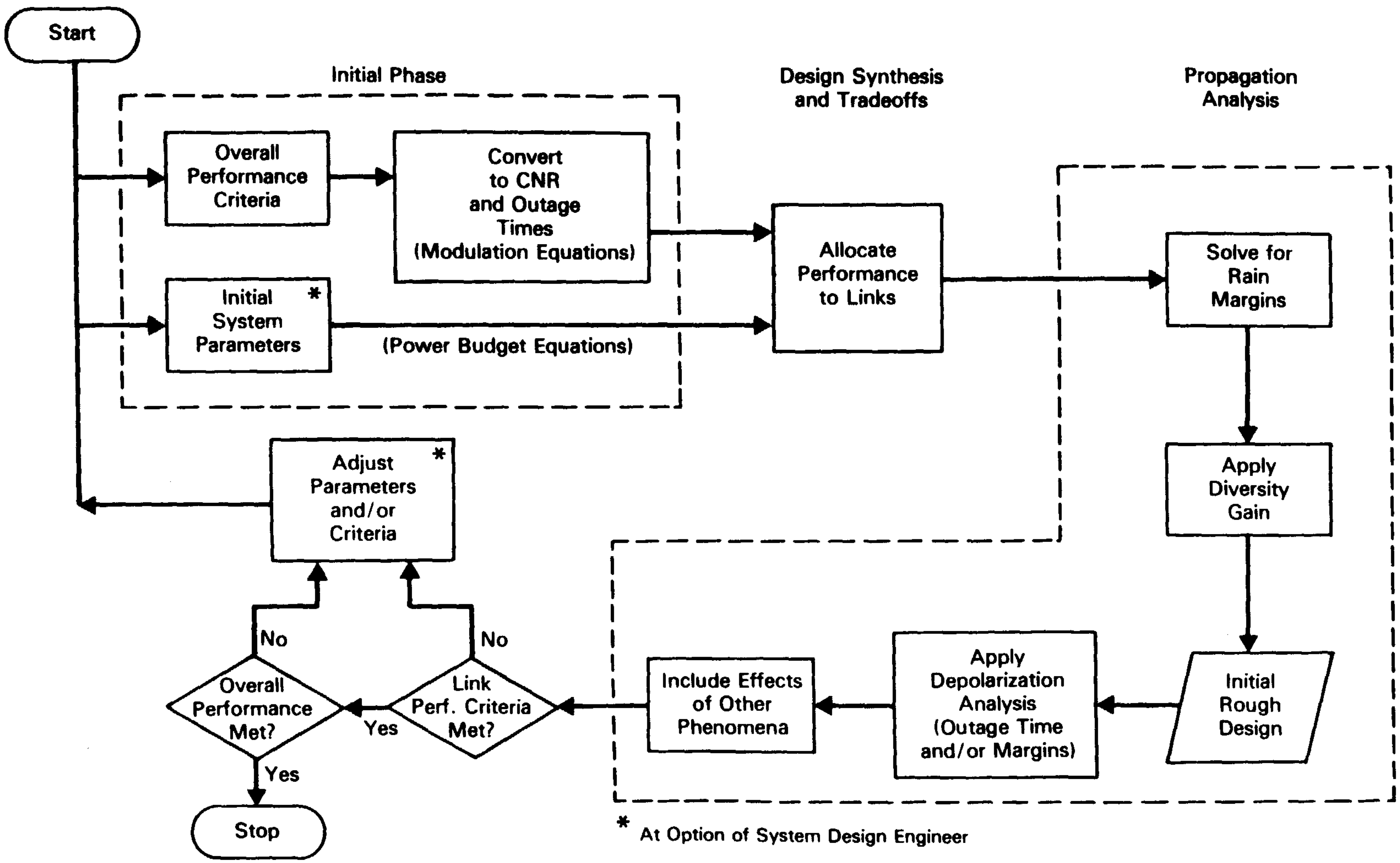

Figure 7.1-1. System Design Process

PROPAGATION ANALYSIS AND ITERATION PHASE

5) Compute rain margins, as reduced by diversity gain, for each path.

6) Adjust system parameters according to margins given by step 5. This gives a preliminary design at the feasibility concept level.

7) Apply depolarization analysis to adjust margins and/or increase the outage time values (% of time for the worst-performance level of the distributions).

8) Consider other propagation effects such as cloud and fog attenuation, signal fluctuations, and antenna gain degradations and add margin to design as necessary.

9) Adjust system parameters to include all additive margins. Analyze system performance, first at the path level, then on the end-to-end performance level.

10) If performance meets requirements closely, stop. Otherwise, adjust design and repeat analysis. If design cannot be made to meet requirements, consider changing requirements.

Performance criteria typically deal with baseband quality, or digital error rates, whereas the power budgets relate physical system parameters to signal-to-noise ratio, CNR, (or equivalents such as S/N, Eb/No, C/kT, etc.). Therefore, the baseband or digital performance criteria must be functionally related to CNR by means of modulation performance equations.

Gross design is performed by means of elementary power budget analysis and free-space (or clear air) propagation characteristics. Basic choices are made at this point, such as selection of modulation and multiple access techniques. It is assumed that the reader is familiar with these techniques and power budget analysis (Northrop-1966). This analysis establishes a relationship between basic system parameters and the signal- or carrier-to-noise ratio (CNR) on a given transmission path.

The system performance requirements, which apply to end-to-end performance, are suballocated to various system components. Most important, the relationship of the end-to-end communication performance to that of each of the links must be determined. For example, the actual received CNR is a composite which may include both uplink and downlink noise contributions. The end-to-end availability involves availabilities of each path.

Since rain induced attenuation is the most severe propagation effect for the frequencies of interest, the next step in the procedure is to calculate a rain margin. If the system uses site diversity, some of this rain margin may be offset by "diversity gain." The remaining margin is then applied to the initial system parameters. Typically, the margin is applied as an increase in power; but it is also possible to increase antenna gains or modify the modulation parameters. At this point, a rough design has been achieved. This level of detail and accuracy may be sufficient if the objective is only to determine system feasibility. For more accurate results, the effects of other propagation phenomena must be considered. Except for depolarization, these effects are generally additive in terms of margin. Loss in crosspolarization isolation (usually termed "depolarization") can be accommodated as an additive term whenever the interference component is small relative to thermal noise and other interference sources. Thus, small degradations such as those due to depolarization from ice are treated as part of the system margin computation*. The more severe degradations in cross polarization such as those caused by rain cannot be counteracted by margin increases. These events will

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*It is not necessary to add margins on a worst case basis. Where large margins have already been included for rain, the ice depolarization event can be assumed to "share" the same margin.

usually be severe enough to cause an outage. Therefore, in systems employing cross polarization isolation, the depolarization phenomenon may reduce or limit the system availability.

Having thus adjusted the system parameters and the performance analyses, the system design engineer can determine whether performance criteria are met, first for the individual link, and then for the overall system. If so, the design process is essentially completed*. If not, the system parameters and/or the performance criteria are modified, and the analysis procedure is repeated. To some, the idea that the criteria are subject to change is disturbing. Within physical (and economic) constraints, it is preferable to modify only the technical system parameters. But there may be cases where the initial performance goals are unrealistic. For example, it simply may not be worth the expense of a large increase in EIRP in order to get a circuit availability of 99.99% for small earth terminals at 44 GHz.

Section 7.2 addresses system performance criteria and examples of representative satellite communication systems, while paragraphs 7.3.1 through 7.3.3 are introductions to general system design procedures. The experienced communication system engineer will probably be familiar with the material covered in these paragraphs, and may therefore skip them without loss of continuity, and concentrate on paragraphs 7.3.4 through 7.3.6, which are addressed to the main issue at hand, namely the specific application of propagation data. Section 7.4 describes several methods for overcoming the effects of rain fades. Diversity schemes and signalling techniques are described that can significantly improve communication performance. Table 7.1-1 is a guide to specific examples contained in this chapter.

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*A fine-tuning iteration may be desirable if the design exceeds requirements.

Table 7.1-1. Guide to Systems Analysis Procedures

7.2 COMMUNICATION SYSTEM PERFORMANCE CRITERIA AND SPECIFIC SATELLITE SYSTEMS

7.2.1 Performance Criteria

7.2.1.1 Introduction

Criteria for communication system performance represent attempts to quantify the "reliability or "quality" of the service. Two methods, applying different probabilistic notions, are generally used. The first method is to regard some indicator of communication quality (e.g., CNR) as a random variable and specify values of its inverse cumulative distribution function, or the probability that a given value is exceeded. With the second method of specifying performance criterion, the quality indicator is taken as a random process, and some statistic of this time-varying process is used. A typical statistic in this case might be the median, mean, or "three-sigma" duration of the periods during which the value stays below a given threshold. If a period during which the CNR is below some threshold is regarded as an "outage", then the criterion would specify outage duration statistics.

The first type of performance criterion, which will be termed availability criterion, is generally specified as the percentage of time that a threshold value is exceeded (or not exceeded), rather than a probability. This is natural, since what we can measure is percentage of time, and not probability. (Ergodicity allows these to be assumed equivalent). Availability criteria are in wide use, and the bulk of long-term performance data analysis has been done from an availability standpoint. However, such criteria and data do not give any information about the time-variation of performance. In many situations, it is desirable to know something about how fast the performance may change. Some temporal information is given by a slightly modified availability criterion, in which a time period is specified. For example, the criterion could state that a given level of noise will not be exceeded for more than a certain percentage of any month. However, the connection between such a criterion and any quantitative temporal description is obscure.

The second type of performance criterion, which expressly describes the temporal behavior, such as mean outage duration, will be termed outage statistics. Besides the outage duration, such statistics might include the distribution function for the time until the next outage, given that an outage is just over. Or they might probabilistically describe diurnal or seasonal performance variations. In the limit, such statistics would give the autocorrelation function or the spectral density of the process. As yet, the available data does not cover a long enough time span to be statistically reliable. We will therefore confine our attention primarily to performance criteria that specify availability, rather than outage statistics.

There are several sources of performance criteria. Among the more generally accepted standards are those promulgated by the International Radio Consultative Committee (CCIR). Telecommunication systems for U.S. commercial use conform to standards similar but not identical to the CCIR's. These criteria are expressed in terms of a baseband noise level (analog) or an error rate degradation (digital) not to be exceeded more than some small percentage of the time in any month (typically, .001 to 0.3%). The Defense Communications Agency has more recently advanced (Kirk and Osterholz-1976 and Parker-1977) criteria based on the probability of occurrence of outage on a five minute call (voice channels), or the error free block probability for a 1000 bit block (data channels).

7.2.1.2 Digital Transmission Performance

7.2.1.2.1 Short Term Bit Error Rate. The primary measure of circuit or transmission quality for digital systems is the bit error rate (BER). Semantically, we use "bit" error rate because the overwhelming majority of digital communications systems transfer binary data streams.* Bit error rate usually applies over a moderately short term, and normally does not incorporate "errors" or outages of duration longer than a few tens of bits.

For most digital systems, the bit error probability can be expressed as a function of the energy-per-bit to noise power spectral density ratio (E_b/N_o). These relationships are available for the theoretical performance of commonly used modulation and coding systems from any good communication theory reference (e.g., Schwartz, et al-1966 and Spilker-1977). The theoretical BEP vs. E_b/N_o relations usually assume white, Gaussian noise. In the presence of

*We should also distinguish between bit error rate, which defines the actual performance, and must be measured by averaging over a sequence of bits communicated, and the bit error probability (BEP), which is a theoretical concept that can apply even to a single bit. BER will be used here, since it is more common, even though BEP is technically more correct.

non-white or non-Gaussian noise, or interference, these relations are not accurate. It is now becoming common to express the performance of actual systems in terms of the E_b/N_o rather than CNR. E_b/N_o is numerically equal to the ratio of signal power to noise power within a (noise) bandwidth equal in hertz to the digital bit rate in bits per second. (Note that bit rate is not in general the same as symbol rate.) For example, the (theoretically ideal) performance of binary PSK modulation requires an E_b/N_o of 9.6 dB for a BER of 10^{-5}.

In the case of digital systems used to accommodate fundamentally analog requirements (e.g., PCM voice channels), there exists a threshold error rate at which circuit quality is considered unacceptable. This threshold value then determines the point at which an "outage" exists. Because error rate is a sensitive function of E_b/N_o , circuit quality degrades quite drastically when E_b/N_o falls below the value corresponding to the threshold error rate. Degradation is not "graceful."

7.2.1.2.2 <u>Digital Transmission Performance.</u> Data communications systems rarely transmit uniform, homogeneous, continuous bit streams. Rather, the data is often formatted in blocks or packets. In many cases, then, the performance requirement is specified in terms of the probability of an error free block, which might typically contain 1000 or more bits. If the only type of transmission imperfection is the randomly occurring bit error process, then the block error performance can be calculated from the bit error rate: Probability of error free block of n bits = $P(\geq 1,n) = (1 - BER)^n$. However, the block error performance may be influenced by the probability of longer outages, losses of synchronization, and the like, which are not usually included in the BER.

In systems used to transfer well-defined messages, other performance criteria may be required. In the most general case where a block is composed of many messages, the system performance requirements could include a message performance criterion, a block transmission performance criterion and a bit error rate. Note that consistency among the various criteria is mandatory. For example, a block error performance of 99% (i.e., 99 out of 100 blocks are error free) for 1000-bit blocks could not be achieved when the bit error rate is 10^{-4}.

In data communications systems where real time delivery is not critical, the concept of throughput is often used. It is implicit that the system involves a return channel path over which acknowledgments and/or requests for retransmission are made. The throughput is defined (Brayer - 1978) as the ratio of the number of information bits transmitted (K) to the total number of bits (including overhead and re-transmissions), n, before the block is accepted. The throughput is approximately

$$K[1-P(\geq 1, n)]/n \qquad (7.2\text{-}1)$$

This approximation for throughput as a function of block error rate applies only when the <u>return</u> channel is error free. Brayer (1978) makes a case for using message delivery delay as the most important criterion, rather than throughput itself. However, they are related closely.

In summary it can be seen that throughput and block error rate are directly related. Bit error rate contributes a major, but not always the only, portion of the block error rate. In communication system design, the (short term) bit error rate or bit error probability is taken as a parameter of analysis and preliminary design. Final performance estimates must, however, take into account both the nominal BER performance, and some consideration of outages. The qualitative relationships among the various criteria are shown in Figure 7.2-1. Notice that the fundamental, or user-requirement- oriented, criteria are on the right side of the diagram, yet the correct logical path for analysis is from left to right. Thus, analysis is employed to <u>demonstrate</u> that a set of system and environmental conditions will meet the performance requirements.

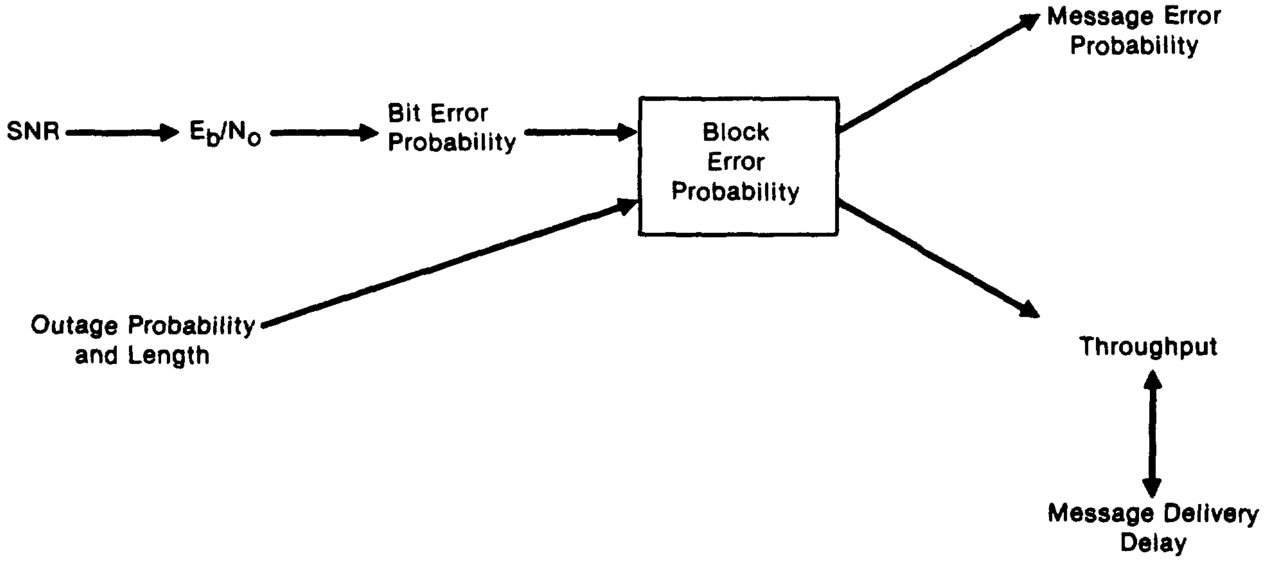

Figure 7.2-1. Data System Performance

7.2.1.3 Analog Transmission Performance

The establishment of performance criteria for analog systems is a complex issue. Transmission system criteria are usually defined on an end-to-end, reference circuit basis. If the satellite system is only a portion of this end-to-end path, a sub-allocation must be made to the satellite segment. Also, when the system is used for relay of multichannel voice trunks, the conversion from baseband (voice channel) performance criteria to the radio frequency criteria (i.e., C/N) involves assumptions about channel loading and modulation parameters. For example, for an FDM-FM system, the noise in picowatts, psophometrically weighted (pW0p), in a voice channel is (GTE-1972)

$$\mathrm{pW0p} = \log_{10}^{-1}\left\{1/10[-\,C - 48.1 + F - 20\log(\Delta f/f_{ch})]\right\} \qquad (7.2\text{-}2)$$